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EFFECTS OF THE FISHERY ON THE NORTHERN QUAHOG (=HARD CLAM, *MERCENARIA MERCENARIA* L.) POPULATION IN GREAT SOUTH BAY, NEW YORK: A MODELING STUDY

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ABSTRACT A numerical bioenergetics simulation model based on the physiological processes affecting individual clams across a range of phenotypes describing a cohort has been developed and applied to the conditions in Great South Bay, New York. The clam population is relatively sensitive to food and to a lesser extent to temperature within this system. The timing of temperature and food in the spring, and more importantly in the fall, can increase population sensitivity beyond the effects of one factor operating alone. The effects of fishing on the stocks in proportion to the size structure present, and as directed fisheries on various size classes (littleneck, cherrystone, chowder) was simulated. Recruitment overfishing was responsible for the stock decline in the 1970s and 1980s, but the continued decline into the late 1990s and 2000s cannot be attributed to fishing alone. Recruit-per-adult declined after the mid 1990s. Modeled stock recovery times under constant environmental conditions are on order of 10–15 or more years depending on the exploitation rate. Under base conditions a proportional fishery that removes approximately 25% of the stock, or a littleneck fishery that removes approximately 37.5% of that size class annually would provide the best economic returns under constant average environmental conditions. Slightly less harvest would be desirable to avoid overfishing in years of less than optimal environmental conditions.

KEY WORDS: quahog, hard clam, *Mercenaria*, fishery, model

INTRODUCTION

The northern quahog (=hard clam) (*Mercenaria mercenaria*) historically supported a large fishery in Great South Bay, NY (GSB), but landings declined dramatically after the early 1980s (Fig. 1). The extent of the fishery and its social, political, and economic importance to the region have been well documented (COMSA 1985, Kassner 1988, Kassner & Squires 1991, McHugh 1991, Schubel et al. 1991). The importance of the fishery to the local economy resulted in collection of substantial data on the biology, ecology, distribution and abundance of this species. Suffolk County, NY, has supported collection of water column data (Nuzzi & Waters 1999), and the towns of Babylon, Brookhaven and Islip, NY, have supported fishery-independent stock evaluations of hard clams in their respective waters. In addition, the US Environmental Protection Agency (EPA) initiated GSB-wide studies during the late 1970s and early 1980s that provide a synoptic evaluation of hard clam stocks and information on potential predators (WAPORA, Inc. 1981, WAPORA, Inc. 1982).

The hypotheses proposed to explain the decline in hard clam abundance in GSB invoke a wide range of potential causes. Overfishing is perhaps the most obvious potential explanation for the decline. Ascribing the observed declines to this single cause may not be correct as other factors may have contributed to produce the present diminished clam population. These other factors potentially contributing to the continued low clam abundance include:

environmental changes that arise from general warming of GSB water due to higher than average winter temperatures,
altered circulation patterns (EPA 1985), change in quantity and timing of freshwater inflow due to installation of sewage treatment plants (Dennison et al. 1991, WAPORA, Inc. 1981),
a change in nutrient loading and composition of GSB waters due to increased treatment of sewage (Dennison et al. 1991, EPA 1985)
modifications to the hard clam food supply through changes in the phytoplankton assemblages and/or phytoplankton production resulting in a reduction in hard clam growth rate,
changes in predation rates and/or predator assemblages resulting from the modified conditions (Polyakov et al. 2007),
a decreased recruitment of clams (Kraeuter et al. 2005).

Recently, attention has been given to the potential effects of brown tide (*Aureococcus anophagefferens*), which appeared in GSB in the mid1980s (Cosper et al. 1987, Nuzzi & Waters 1989). The occurrence of blooms of this toxic alga may result in reduced feeding of adult clams and thus reduced fecundity and reduction in growth rate of juvenile clams (Greenfield et al. 2002, Bricelj et al. 2004). These reductions may make them more susceptible to predation or starvation. In addition, reduced growth or starvation of hard clam larvae (Bricelj & MacQuarrie 2007, Padilla et al. 2006) may affect recruitment.

Modeling provides one approach for investigating the potential for multiple variables and/or their interactions to reduce hard clam populations and to identify and scale the effects of these factors, working singly or in combination. This

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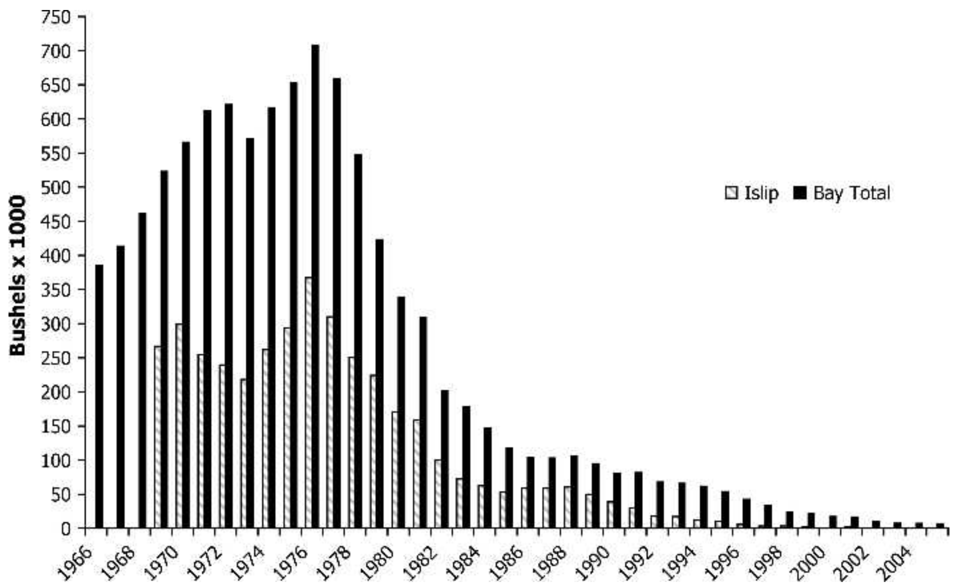

Figure 1. Hard clam (*Mercenaria mercenaria*) commercial landings from Great South Bay and those limited to the Islip, NY region.

study uses an existing model that was developed to simulate the growth and development of hard clams in GSB (Hofmann et al. 2006) to investigate the effects of fishing on the hard clam population. The focus is on fishing, because this is the most cited reason for the decline in GSB hard clam populations. The effects of other factors such as environmental variability and brown tide can then be scaled relative to that of fishing. The extensive fishery-independent data sets on hard clam abundance collected by the Town of Islip and the GSB hard clam landings data (Fig. 1) are used to evaluate the simulation results.

Background and Data Sets

Great South Bay

Great South Bay is a shallow (mean depth ~2 m), high salinity estuary with sand as the dominant (95%) habitat, but with local areas of muddy substrate near river mouths, and areas of eelgrass (*Zostera marina*) near the islands along the southern shore (Polyakov et al. 2007). Much of the early physical and biological data for GSB have been summarized by Schubel et al. (1991). The estuary has high phytoplankton production with average values of 450 g C $m^{-2}yr^{-1}$ (Carpenter et al. 1991). Since the middle 1980s there have been repeated blooms of *Aureococcus anophagefferens* (brown tide) (Cosper et al. 1987, Nuzzi & Waters 1989, Nuzzi & Waters 2004). Because freshwater input into the system is limited, historic salinity changes have been dramatic and based on the opening, closing and stabilization of inlets (Schubel et al. 1991). Historically, openings and closings, among other perturbations, have caused significant changes in hard clam and oyster stocks. The most significant event responsible for the increase in clams stocks took place in 1931 when a new inlet formed in Moriches Bay and increased salinity in the eastern part of GSB (McHugh 1991). Stabilization of GSB inlets began in 1940 when rock jetties were built at Fire Island Inlet and in 1958 at Moriches Inlet. These stabilizations have maintained the bay salinities at the higher end of the historic spectrum (McHugh 1991).

MATERIALS AND METHODS

Great South Bay Hard Clam Fishery

The fishery for hard clams in Great South Bay is conducted by individual baymen from small boats using either clam tongs or rakes to harvest the clams (Kassner & Squires 1991). Licenses for commercial or recreational clamming are issued by the Town of Islip, but only landings by commercial harvesters are recorded by the State. The number of licenses generally follows the abundance of clams (Fig. 2), but in all likelihood, most of the clams are harvested by relatively few individuals, who work full time on the water and rely on the hard clam for a significant portion of their income (Conrad 1982, Kassner & Squires 1991). Commercial licenses peaked in 1976 at 2325 (Fig. 2). By 2001 a nearly 10-fold drop had occurred and only 227 commercial harvesters were licensed. At one time a significant recreational fishery was also present in GSB. In the Town of Islip, 2525 recreational harvesters were licensed in 1975, but these too declined so that by 2001 only 299 permits were sold (Fig. 2). The license data for Islip mirror those of the other towns surrounding GSB. It is difficult to estimate the numbers of commercial or recreational harvesters who are not licensed, but it is likely that this could be significant.

Hard Clam Sampling Methods

The data from the Town of Islip provide the longest and most comprehensive survey that is available for hard clam abundance and distribution in GSB. Thus these data are assumed to be representative of the hard clam population conditions in GSB, and landings data (Fig. 1) indicate that Islip is representative of bay-wide harvest trends. Islip has about 6,000 hectares of bay bottom under its management. Historically, 80% of the Town's waters were open for harvest of clams (certified), 10% were closed because of pollution (restricted or prohibited), and 13% were leased. Since 1978, Islip has conducted an annual, fishery-independent survey of its clam

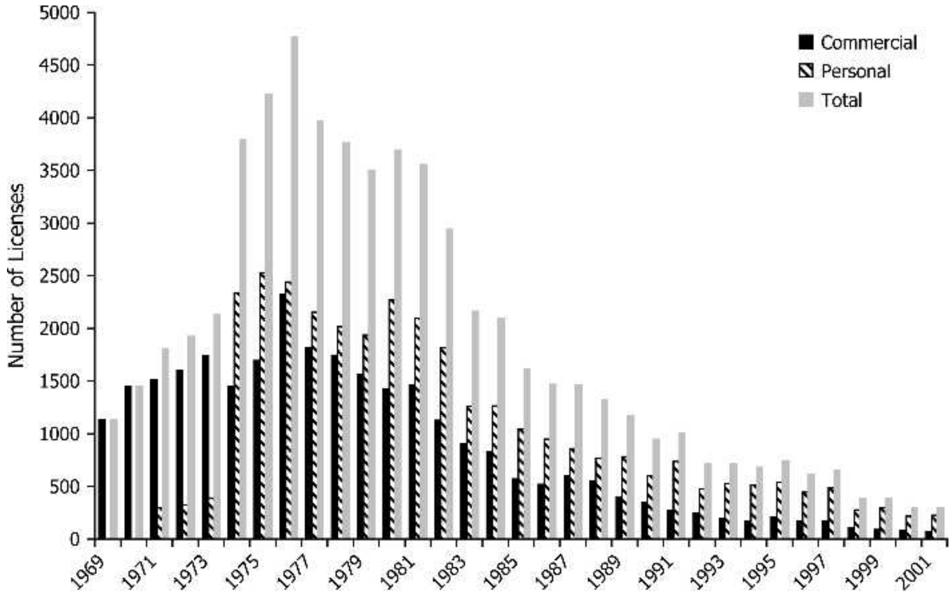

Figure 2. Hard clam (*Mercenaria mercenaria*) commercial and personal licenses issued by the town of Islip, NY.

populations (Buckner 1984), and methodology has remained relatively unchanged since its inception. The survey is based on a grid system in which town waters (approximately bounded by 40°39′N, 73°17′W, 40°43′N, and 73°10′W) are divided into grids 400 m on each side. Duplicate grab samples were removed from a randomly chosen area within each grid. The number and sizes of all live clams and all articulated valves were recorded. The survey was typically conducted using a barge with a commercial clam shell bucket that removed between 0.68 and 1.51 m^2 of bottom (Table 1). In most years, either a 0.94- or a 1.02-m^2 bucket was used. In years in which a smaller ~0.68-m^2 bucket was used, four rather than two grabs were obtained from each station so the amount of bottom sampled remained approximately the same. Duplicate samples at each station were sieved through a 6.4 mm square mesh sieve. This was changed in 1985 when the use of a sieve with round perforated stainless steel holes 3.2 mm in diameter was instituted. For all samples, the numbers were adjusted to a 1-m^2 basis for analysis. All live and dead clams were enumerated, and all live and dead clams were measured with a caliper to the nearest mm. From the thickness measurements clams were separated into seed (ages 0, 1, and 2), submarket, and various commercial size classes that correspond to littleneck (48–66 mm shell length), cherrystone (67–76 mm SL) and chowder >76 mm SL). From time to time specimens have been set aside for shell sectioning and aging of the animals (Buckner 1984 [Islip], Wallace 1991 [Brookhaven], Laetz 2002 [Islip]). The Islip data clearly show a decline in hard clam stocks beginning at the time of the initiation of the survey (Fig. 3).

The Model

Details of the bioenergetic-based numerical model (Fig. 4) developed for hard clams are given in Hofmann et al. (2006). Only a summary is given here. The model is based on the assumption that changes in shell size are related to animal condition (dry meat biomass/length). Soft tissue weight and length were calculated independently over time, which allowed a clam to increase in weight without a corresponding increase in length. The simulated weight was compared with an average weight for a given length derived from empirical data. This estimate of animal condition was then used to indicate the condition of the modeled animal. An increase in length could only occur for positive condition.

The hard clam model includes the physiological processes affecting growth and development of an individual clam, and these are modified by environmental conditions of temperature, salinity, food (chlorophyll a), total suspended solids and brown tide concentration. The environmental condition affected filtration, which increased with clam size and temperature but was reduced outside optimum temperature and salinity ranges. Physiological rates were based on clam age and condition. Respiration was the primary metabolic loss and net production was apportioned into reproductive and somatic tissue with the relative allocation being a function of temperature and clam size. For clams <30 mm all production was allocated to somatic tissue.

Daily specific natural mortality rates included in the model were specified to give high, low and moderate levels for small, early adult and older clams, respectively. Reproductive tissue was produced when net production and condition were positive and ambient temperatures were favorable. Spawning occurred when reproductive tissue reached a specified fraction of body weight and condition was positive. The parameterizations for each of these processes are detailed in Hofmann et al. (2006).

The model was initialized with a clam of average size (for GSB) on January 1 of the clam's second year. Early in life, condition; net growth efficiency; and somatic growth were high (Fig. 5), and by year 3 some animals reproduced. As animals aged, condition and reproduction began to decline because more energy was required to maintain the larger biomass. This relationship caused a reduction in the egg production per unit of biomass. The coupling of this reduced egg production per individual with the increased mortality of older clams (see

TABLE 1.

Historic record of number of stations and grab size used in obtaining hard clam (*Mercenaria mercenaria*) data for the Town of Islip, NY.

Year	Number of Stations	Grab size m^2
1978	402	1.03
1979	392	1.03
1980	305	0.68
1981	336	0.68
1982	288	1.02
1983	309	0.84
1984	295	1.02
1985	313	1.02
1986	311	1.02
1987	311	1.02
1988	314	1.02
1989	305	1.02
1990	308	1.02
1991	305	1.02
1992	303	1.02
1993	337	0.94
1994	340	0.94
1995	335	0.94
1996	333	0.94
1997	339	0.94
1998	353	0.94
1999	340	0.94
2000	341	0.94
2001	382	0.94
2002	341	1.51
2003	381	1.51
2004	337	0.929

below) resulted in a decrease in their contribution to recruitment (Hofmann et al. 2006, Fig. 14, see later).

Results from the individual-based model were scaled to the level of cohorts and populations using probability distributions, based on a Gaussian distribution, that were based on the range of variability in hard clam respiration rate and assimilation efficiency. This process is introduced into the population *via* the observed variability in size at age. Clams varied in their growth efficiency as determined by variations in assimilation and respiration so that the cohort comprised a range of 64 phenoytpes (8 assimilation × 8 respiration types). The scaling to cohort and population level used a basic stock recruitment function that was based on information derived from the Islip population parameters (Kraeuter et al. 2005).

Hard Clam Population Statistics

License sales and fishery-independent hard clam population surveys indicate a decline in clam populations along with landings (Figs. 2 and 3). Harvest data from Islip included the numbers of clams in various market categories (e.g., littleneck, cherrystone, and chowder). The Islip survey data were recorded as the size of individual clams, but bracketed into the various market categories as well as prefishery-recruits. This allows direct comparisons to be made between the two data sets.

The Islip survey data (Fig. 3) show that hard clam total abundance has declined from the earliest period (7.76 m^{-2} in 1978) to present (1.04 m^{-2}) and that littleneck and larger clams have declined from 4.1 m^{-2} in 1978–1.04 m^{-2} at present and recruits have declined from 3.66–0.24 (47% *vs.* 23% of the total). Since the earliest period, and until the late 1990s, the numbers of smaller size clams declined, whereas cherrystone and chowder sizes have remained relatively constant. Littlenecks comprised the most abundant adult size class (40% to 76% of adults) until the late 1990s. Starting in the mid 1980s the rate of decline of age 1 and 2 clams increased relative to the other size classes. This decline continued, but mortality on the age 2–4 clams increased in the mid to late 1990s. An appreciable decline in larger clam sizes became apparent in the mid-1990s and continues to the present. The hard clam abundance data consistently suggest (although often not statistically significant) that more age 2 clams exist in the population than age 1 clams even though the sieve size used retains all clams age 1 and greater (and some fraction of age 0 individuals). Inadequate survey density or survey bias does not explain this trend (unpublished data) which remains perplexingly unexplained.

Fishery data on hard clams typically under-report actual landings and GSB is no exception (Mirchel 1980, Buckner 1984,

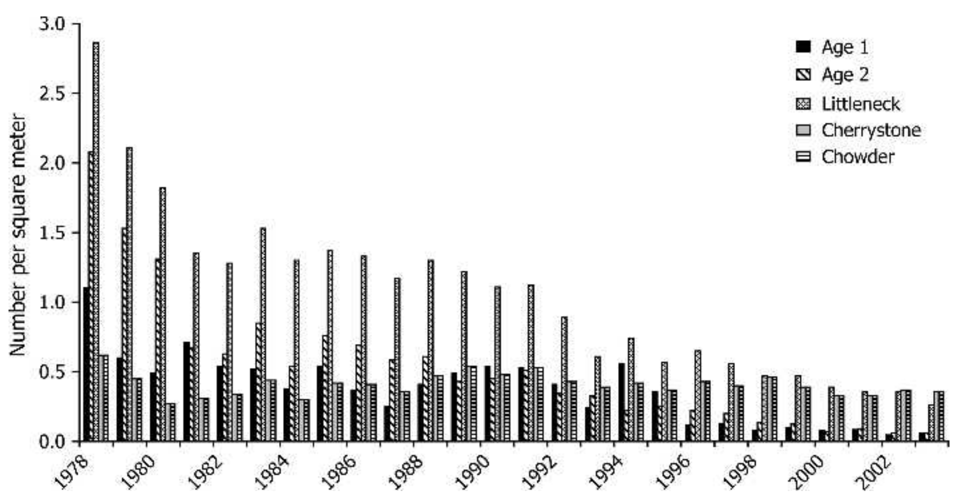

Figure 3. Survey abundance of hard clam (*Mercenaria mercenaria*) size classes in Islip town waters of Great South Bay, NY.

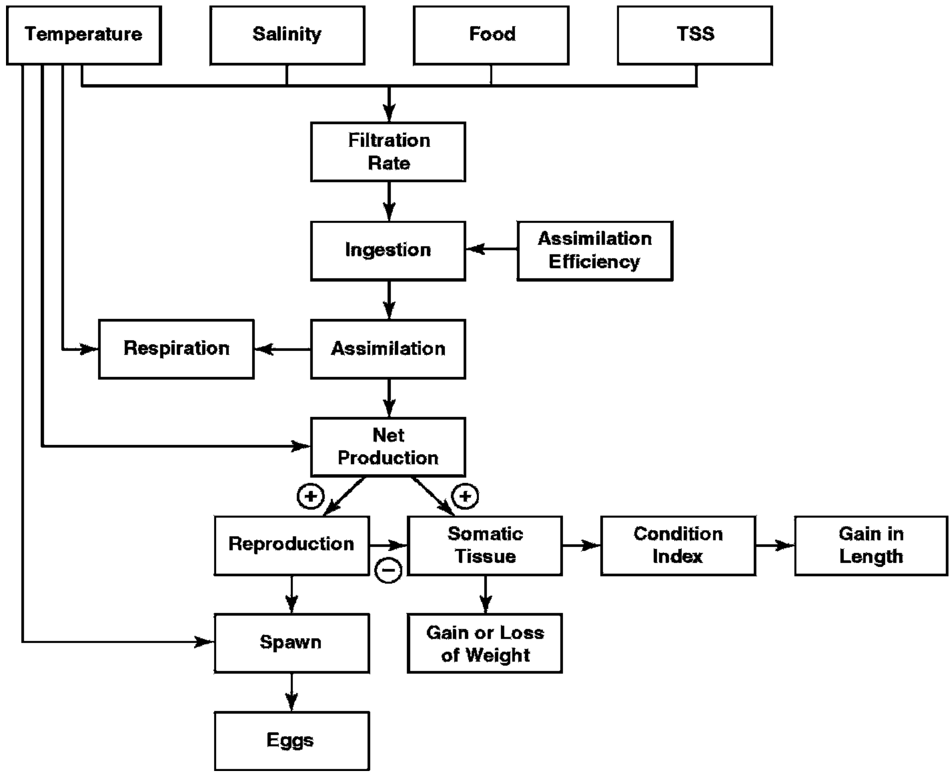

Figure 4. Schematic of the processes and transfers included in the individual-based hard clam model. TSS = total suspended solids, The allocation of net production is determined by temperature, animal weight and animal condition. Positive net production (+) results in formation of reproductive and somatic tissue. Negative production (–) results in the resorption of somatic tissue.

Kassner & Squires 1991, McHugh 1991). Fox (1978) evaluated the recreational landings in GSB and found that they were >1% of the commercial production. Because recreational harvest data are less affected by effort than commercial landings it is probable that this percentage increased as commercial landings declined. Mirchel (1980) found that managers and enforcement personnel believed that 25% to 50% of landings in GSB were from prohibited waters (those not meeting bacteriological standards for harvesting shellfish for human consumption). Based on these data Mirchel (1980) estimated that between 25% and 35% of GSB landings were from illegal harvests. Buckner (1984) estimated that the illegal harvest from prohibited waters amounted to 16% of the commercial landings. What is not evident from these data is what percentage of the harvest from prohibited areas is included in the landings data, and what percentage of the recreational harvest is from prohibited waters. In addition, there is still a significant recreational fishery, and under low population abundance, the number of licenses may not reflect the actual numbers of recreational fishers. What is clear is that a significant percentage of the harvest may not have been or may not be reported.

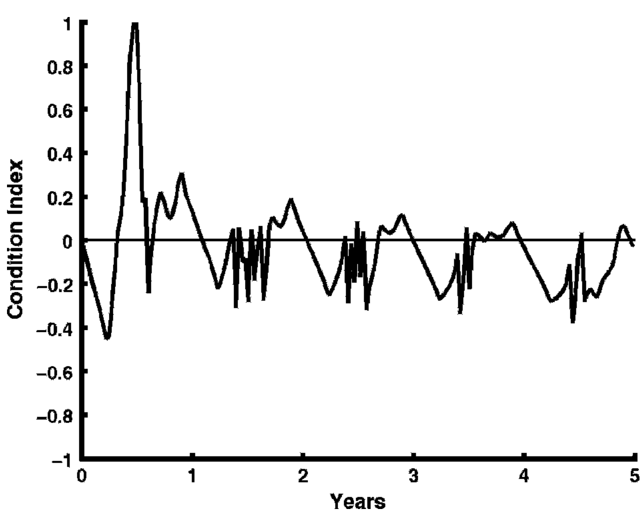

Figure 5. Five-year simulation of clam condition relative to the mean value of 0.00. Condition was estimated by comparing the model length-soft tissue dry weight output with an average length-weight relationship based on literature values. Positive condition (above the 0 line) indicates accumulation of somatic and/or gonadal tissue. Negative values (below the line) indicate resorption or loss of gametes primarily in winter. Spawning is indicated by the sharp vertical transgressions.

Recruitment overfishing in hard clam populations has been reported in North Carolina (Peterson 2002) and in GSB (Buckner 1984). In spite of the high potential for substantial under-reporting of commercial harvest and the lack of recreational harvest data, the possibility that recruitment overfishing was taking place in GSB was evaluated by dividing the numbers of prerecruits for both ages 2 and 3 by the numbers of clams harvested (Fig. 6). Recruitment overfishing of GSB hard clam populations was prevalent from the late 1970s to at least the early 1990s (Fig. 6). From 1978 until 1988, in only one year were fewer clams removed than were supported by sufficient numbers of 1 y-old recruits to replace them. For 2-y-old clams the 100%

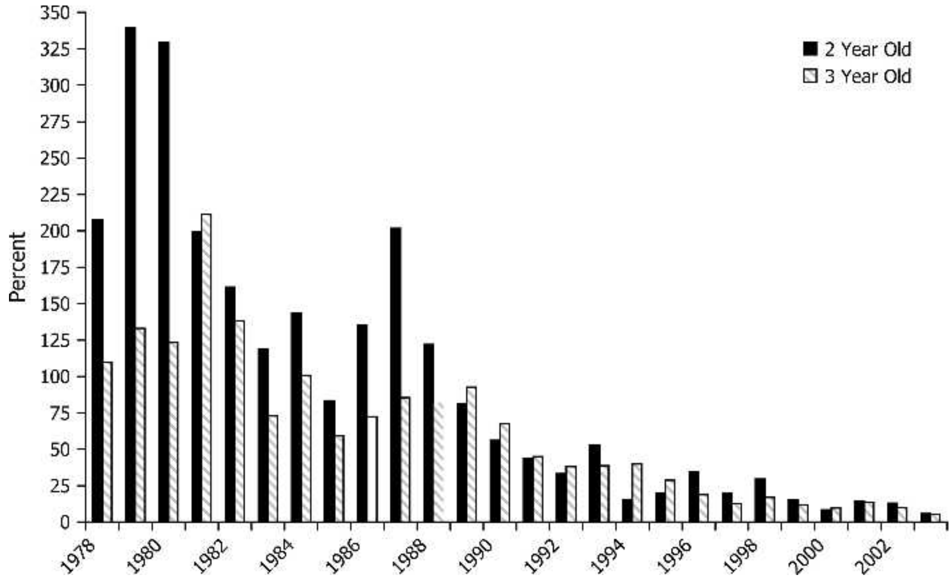

Figure 6. Harvest as a percentage of potential recruits. Recruits are defined as clams that have reached their first (2 y old) or second (3 y old) year in the field.

threshold was reached in 6 of the 11 y. Fishing pressure did not decrease to below 25% of recruitment until 1994 (2-y-olds) and 1996 (3-y-olds). Although overfishing seems to be responsible for the declines in the 1970s and 1980s, reduction in recruitment success seems to have exacerbated the decline beginning in the mid1990s (Fig. 7). Even though the numbers of small clams are declining in this population, because it was already being heavily overfished at the beginning of the time series, they make up a high proportion of the total stock. This skewed size distribution is additional evidence for overfishing (Rice et al. 1989, Fegley 2001). In unexploited populations of long-lived animals the age structure is typically shifted towards older organisms (Johnson 1994), and evidence suggests that this is also true for hard clams (Fegley 2001).

Model Simulations

The effects of the severe overfishing on GSB hard clam populations suggested by the landings and survey data were evaluated with the hard clam model. Specifically, simulations were done to focus on the response of the three commercial size classes (littleneck, cherrystone and chowder) and to assess the effects of a fishery closure *versus* some continued level of fishing on the recovery of the population. Model output is in terms of biomass or numbers m^{-2}, and in both cases these represent only the standing stock of clams >30-mm shell length. Before assessing the effect of fishing it was necessary to establish base simulations that provide a reference to which the fishing simulations can be compared.

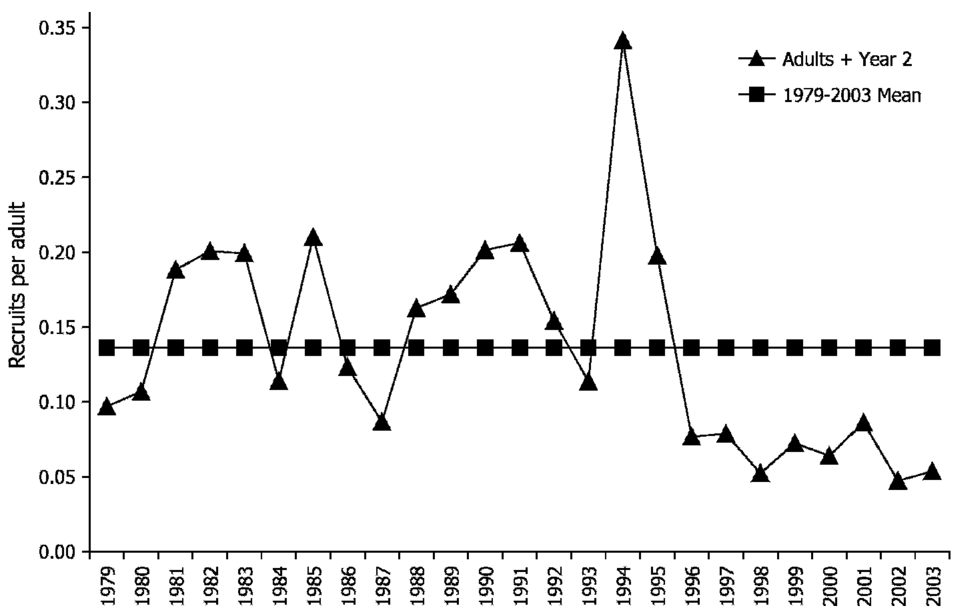

Figure 7. Recruits per adult. Horizontal line is the 1979–2003 average for recruits per adult. Adult clams = all animals 2 y old and older.

Base Cases

The environmental conditions chosen for the three base cases correspond to: (1) average food conditions measured in 1985 (Quaglietta 1987) and "typical" temperature condition measured in 1978, a year with a typical cool winter (Bricelj 1979), (2) low food condition measured in 1986 (Quaglietta 1987), and temperature measured in 1998 (Nuzzi & Waters 1999) a year with a typical warm winter, and (3) an average food year (1985) and a warm winter (1998). Salinity and total suspended solids (TSS) were not altered because there were either limited data or the data do not indicate substantial change from the middle 1970s to present. Effects of brown tide on hard clam populations from GSB were excluded from the fishing simulations but are the subject of a companion study (Bricelj et al. in prep).

The simulated hard clam population, as individuals m^{-2} and biomass m^{-2}, was more sensitive to low food conditions than to warm winters (Fig. 8). Warmer conditions increased populations even with the same food levels. Continuous low food conditions, such as those in 1986, decreased the numbers and biomass to the point that fishing would become uneconomical. It is important to emphasize that correspondence, or lack thereof, between temperature and food supply can magnify or reduce these responses. It is also important to emphasize that the simulations of low food or other conditions represent an unusually severe case as the model simulates a continuous series of years under these conditions. Typical temperature and food conditions vary considerably from year to year and thus the poor conditions would only represent a minor deviation from the long term average.

The average food level (1985) and "typical" cool winter (1978) combinations were selected as the base conditions for the fishing simulations presented in the following sections. Modifications to fishing mortality were begun in year 10 of the simulation. This ensured that the simulated adult hard clam population had reached a stable distribution (Hofmann et al. 2006) and thus changes from the base conditions for the next 40 y result from model dynamics and conditions being investigated.

Fishing Simulations

The modeling of fishing on the model clam populations can be done using a wide range of approaches. In this study, the effects of continuous removal of various segments of the population were first simulated. Additional simulations considered the effects of heavy fishing for 10 y followed by 30 y of recovery, with either complete or partial cessation of the fishery, on the population. To achieve stability the fishing simulations were run for 50 y and the results, as population numbers and biomass, are compared with those from the equivalent base case that does not include fishing effects.

Proportional Fishing

The effect of proportional fishing, in which each hard clam size class is harvested in proportion to its abundance was simulated with 10% to 75% removal of harvestable stocks beginning in year 10 (Fig. 9 a,b). In the late 1970s and early 1980s, littleneck clams were the most abundant size class in GSB and this fishing strategy would have yielded a high proportion of littlenecks (the prime market size) (Fig. 1). If the environmental conditions remained constantly favorable as in this simulation, and 25% of the adult population was removed annually, the standing stock would show an immediate decline from 3.9–2.6 clams m^{-2} (biomass 7.9–3.3 g m^{-2}) and then remain relatively stable. Fishing at 37.5% caused a continuing drop in the population and biomass for each of the 40 y simulated.

Size Class-Based Fisheries

The effects of four other potential fisheries in which harvesting was applied only to littleneck, topneck (an intermediate size class formed from large littleneck sizes), cherrystone and

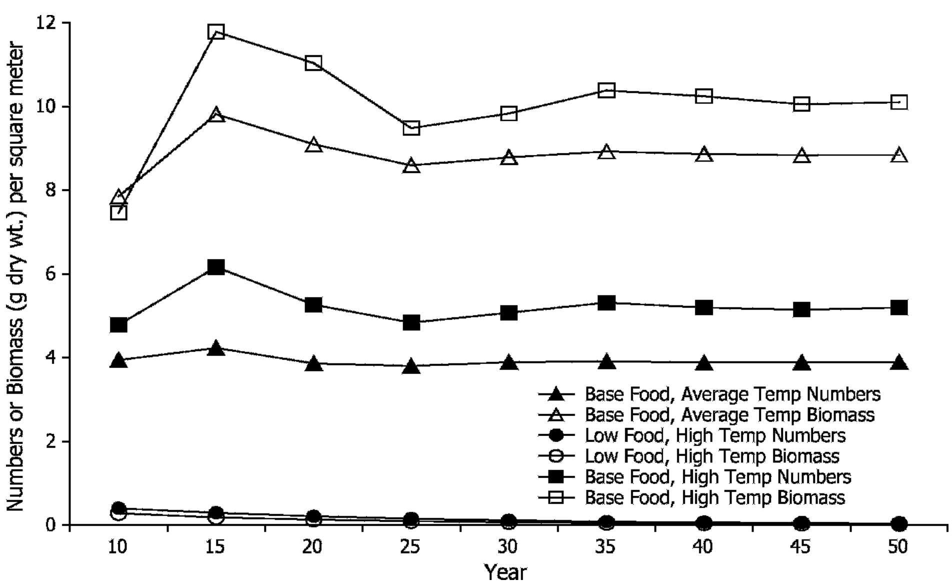

Figure 8. Simulated model output for numbers of individuals or biomass (grams dry weight of meat) m^{-2} under various combinations of temperature and food levels. See text for source of the food level and temperature data.

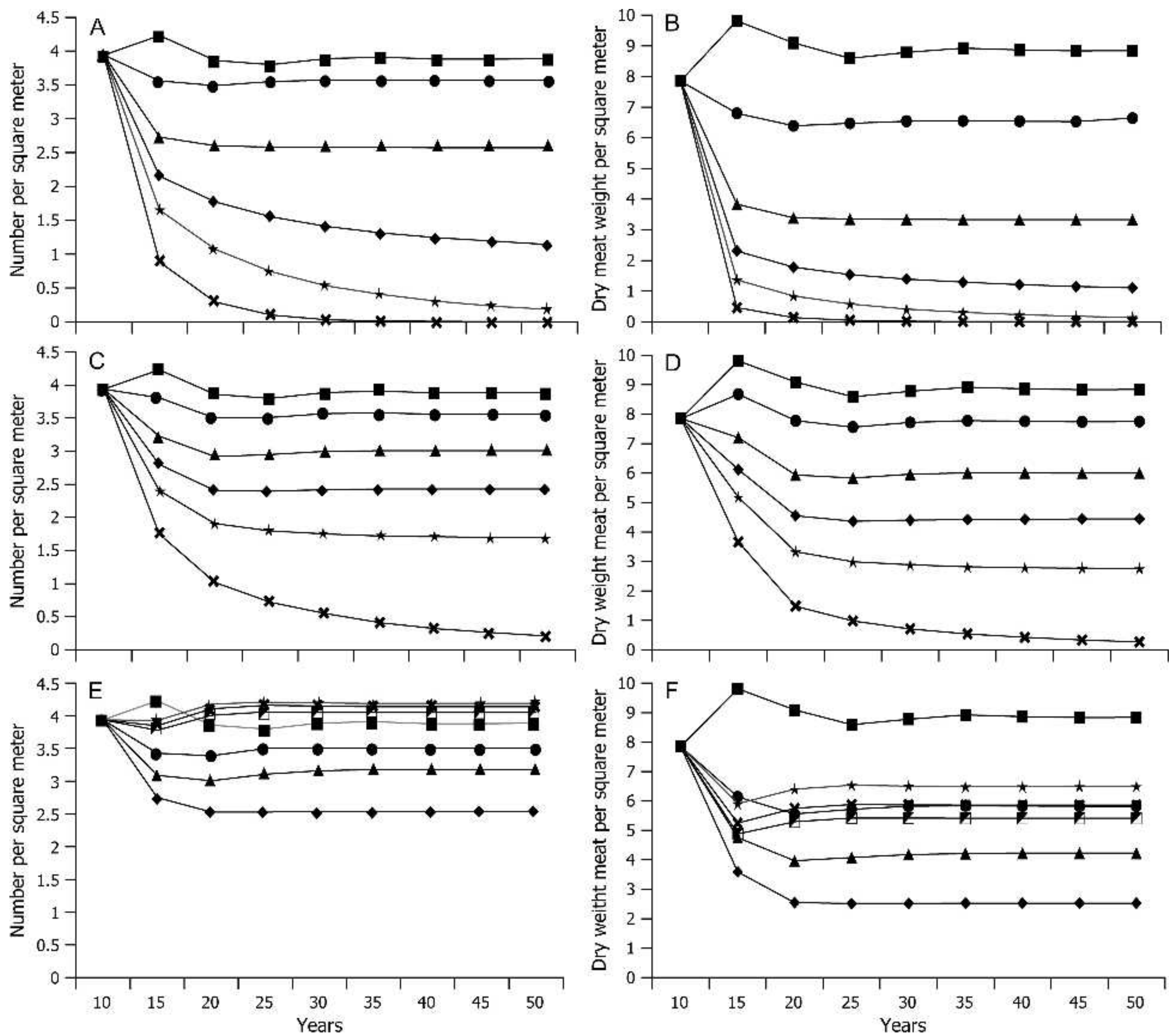

Figure 9. Simulated effects of fishing on clam populations in the waters of Islip town, NY. Base = base conditions with no harvest. Percentages indicate the percent of the stock removed annually for the number of years indicated. Graph pairs are for numbers and dry meat weight m^{-2} remaining. The left column (A,C,E) = numbers and the right column (B,D,F) = biomass. (A) and (B) = a fishery removing clams in proportion to their size abundance. (C) and (D) = a fishery removing only littleneck sized clams. (E) and (F) = a fishery removing only cherrystone size clams. Percentage symbols apply to figures A, B, C, and D. Symbols for E and F (circle, triangle and diamond = 50, 75, and 100% cherrystone), (star, cross, and two-color box = 50, 75, and 100% chowder), and the base remains the same. Legend: ■ Base, ● 10%, ▲ 25%, ♦ 37.5%, ★ 50%, ✕ 75%, ◩ 100%.

chowder sized clams were simulated. A littleneck-only fishery was similar to the proportional fishery in its effects on the clam population at 25% fishing, with numbers and biomass declining from 3.9 clams m^{-2} and 7.9 g m^{-2} to 3.0 clams m^{-2} and 6.0 g m^{-2}, respectively (Fig. 9 c,d). In contrast to the proportional fishery, fishing on littleneck clams at 37.5% did not force the population into a long-term decline.

Simulated fishing on topneck clams (not illustrated), not surprisingly, yielded a reduction in the numbers of clams m^{-2} intermediate between that of littleneck and cherrystone fisheries. Removal of more than 50% of the topneck standing stock per annum began to reduce yields to the fishery and resulted in a continuing reduction in the clam population.

Simulations of fishing only for cherrystone or chowder size clams (Fig. 9 e, f) caused an immediate small reduction in the clam population. Removal of 100% of the cherrystone clams caused only a 25% decline in clam numbers, but a 68% decline in standing stock biomass. Removal of 50% to 100% of the chowders caused a slight increase in numbers above the base population. Biomass changes, whereas not as severe as those caused by proportional or littleneck fisheries, were more substantial than the decline in numbers. A 100% fishery on chowder size clams caused a 31% decline in biomass. Under the simulated conditions, fisheries focusing on either of the larger size classes could remove nearly all clams in the size class and continue indefinitely.

Population Recovery

The time required for a heavily fished population to recover to its base level was evaluated for different fishing strategies. The base case remained the same as under the other simulations. In the first simulations, adult clam populations were exposed to a 50% proportional, or a 50%, 75%, or 99% littleneck fishery for 10 y and were then allowed to recover without further fishing (Fig. 10a). Stocks reduced from nearly 4 clams m^{-2} to 1 or 2 clams m^{-2} under the 50 and 75% littleneck fishing rates, respectively required approximately 10 y to recover. Fishing at the 99% littleneck rate reduced the population to <0.5 clams m^{-2}, and recovery took nearly 15 y.

Recovery from a similar 50% littleneck or proportional reduction, but with a continued fishery removal of 10% per annum, requires 10–15 y (Fig. 10b). The decline from a 50% littleneck fishery followed by a continuing 25% fishery also reached a stable point in 10 y, but at a population level that is about 1 clam m^{-2} less than the base population (Fig. 10b). Removal of littleneck clams at 99% for 10 y resulted in a very low simulated adult population, and recovery times of 20–25 y under continued 10% or 25% littleneck fishing (Fig. 10b), respectively.

Effects of Broodstock-Recruitment Curve and Recovery Times

The development of populations from the simulations was dependent on the broodstock-recruitment relationship. Thus, sensitivity of the population that developed using a constrained relationship (C) that decreased recruit output per unit biomass

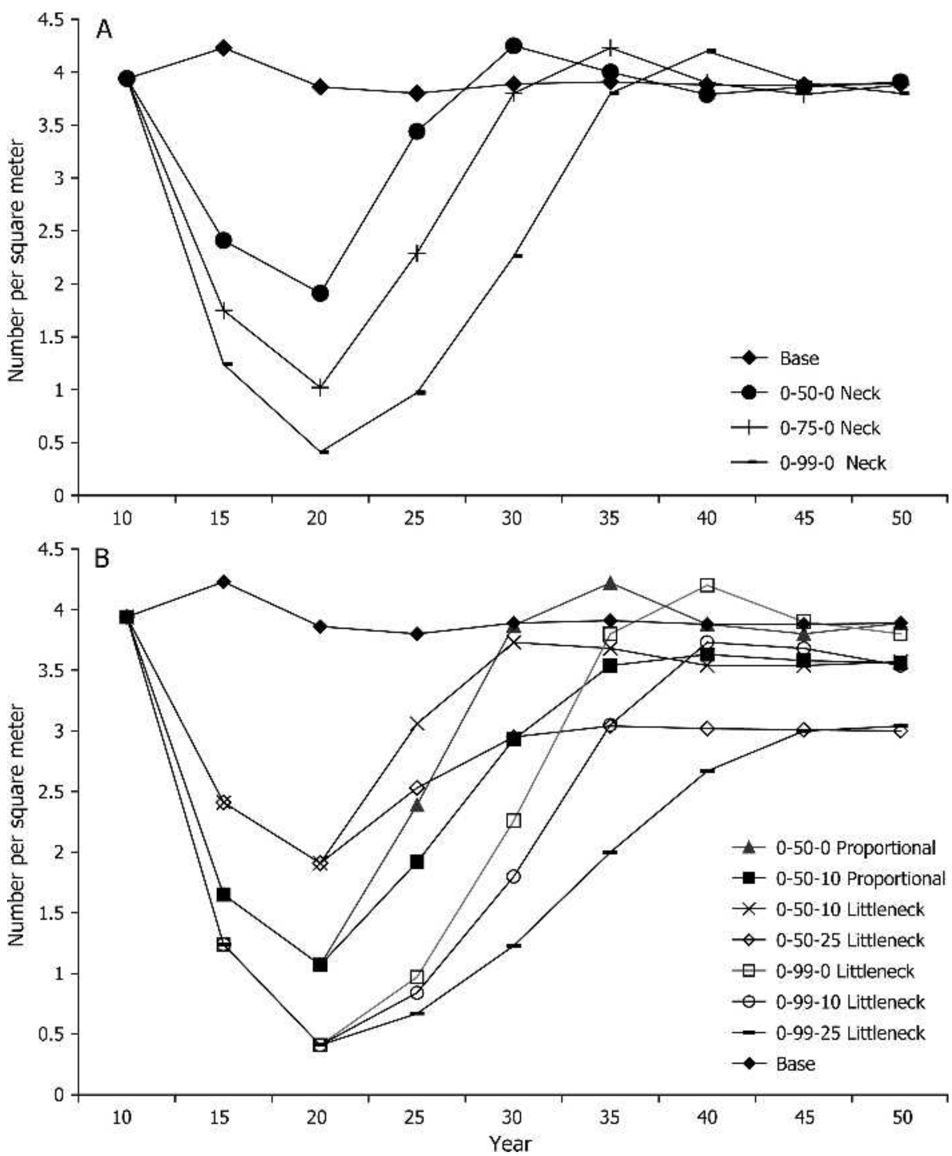

Figure 10. Simulated recovery curves for a hard clam population fished at 50, 75 or 99% of the littleneck sized clams for 10 y and then allowed to recover. Base = base conditions with no fishery. Recovery under conditions of no fishing (Fig. 10 a) for the time of recovery, and continued fishing (Fig. 10 b). Fig. 10 a symbols are 0-50-0 = no fishing for 10 y, 50% fishing for 10 y, 0 no fishing for recovery period. Fig. 10 b symbols are 0-50-10 = no fishing for 10 y, 50% fishing for 10 y, 10% fishing for recovery period. In Fig. 10 b, effects on both a littleneck and proportional (prop) fishery are depicted. The type of fishery did not change during the simulation.

by approximately 25%, and a relaxed relationship (R), that increased recruits by a like amount was investigated. Clam populations were subject to 99% littleneck fishing for 10 y and then allowed to recover under the relaxed and constrained conditions with a continuing 25% littleneck fishery (Fig. 11). Simulated recovery rates to the new stability point took approximately 25 y, and the relaxed or constrained broodstock-recruitment relationship had no effect on the rate of recovery (Fig. 11). Relaxing the broodstock-recruitment relationship allowed the population to reach an average density approximately 0.6 clams m^{-2} higher than the 25% fishing base case, whereas constraining this relationship reduced the population by a like amount (Fig. 11). These results suggest that shifts in the location of the population stable point of ±0.6 clams m^{-2} may be caused by errors associated with estimates of the broodstock-recruitment relationship but that larger changes can be interpreted as characteristic of other factors such as changes in environmental conditions or population characteristics.

DISCUSSION

Little doubt remains that the decline in the GSB hard clam populations in the 1970s to at least the late 1980s was the result of overfishing (Buckner 1984, Kraeuter et al. 2005). From 1978–1998 the littleneck and larger sized hard clam population in the Islip part of GSB declined from 4.1 m^{-2} to 1.24 m^{-2} (approximately a 45% decline in each decade), whereas the landings fell nearly 98% (from 251 $\times$ 10^3 bu. in 1978–3.5 $\times$ 10^3 bu. in 1998). The decline in landings was approximately 76% for the first decade but accelerated to 94% during 1988–1998. Commercial and personal licenses fell by 69% and 62%, respectively, for the first decade and then dropped an additional 80% and 64%, respectively during the second decade. Reduction in the commercial (94%) and personal (86%) licenses issued by the town suggests that fishing pressure has been greatly reduced. The percentage of the clam stock harvested (Fig. 12) also suggests that currently fishing is much less important, but we cannot exclude the potential for significant illegal harvests.

If a proportional fishery is assumed to have existed throughout the time represented by these data, over the first 15 y, simulating removals at a 37.5% per annum suggests that fishing can account for most if not all of the observed decline in numbers (Fig. 13). After this initial decline, fishing rates would have to exceed 50% to account for the precipitous decline in the last 10 y of the time series. This rate is not supported by the data (Fig. 12) for this time period. The model suggests that fishing rates on littlenecks at >50% would be required to account for observed landings (Fig. 12). The time series suggest that some factor(s) other than fishing is responsible for the continuing decline in the hard clam population in the 1990s. This is particularly evident in the reduced contribution of the smallest size clams to the overall population numbers (Fig. 3). A cursory analysis of the data by comparing the change in average numbers from 1978–85–1996–2003 periods shows that the smallest size class collected (age 1) has dropped 40%. For age 2, 3, littleneck, cherrystone and chowder sizes the drop has been 79%, 72%, 56%, 39%, and 12% respectively. This suggests that it is not the abundance of chowders or the smallest size that is the factor limiting recovery, but something that reduces the intermediate sizes.

Anecdotal evidence indicated that hard clam growth rates have declined in recent times. Studies by Laetz (2002) using experimental plantings of seed and archived shells suggest a slight drop in average growth after 1992, possibly causing a 6-mo longer period to harvest, but the differences were not

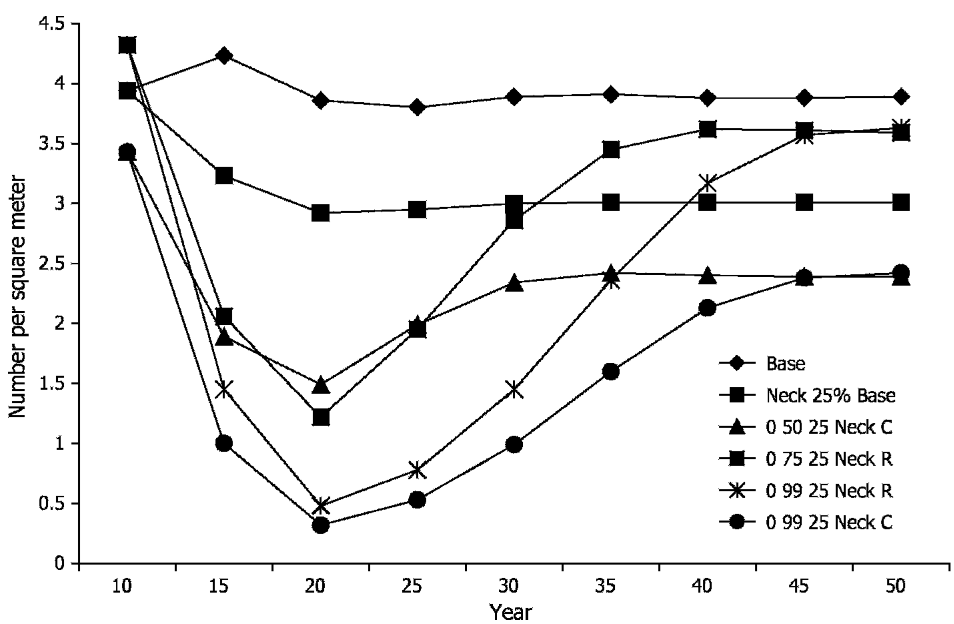

Figure 11. Simulated recovery curves for a hard clam populations fished at a rate of 99% removal per annum of littleneck size-class clams with a recovery starting in year 20. Base = base conditions with no fishery. Neck (= littleneck). Neck 25% base = base conditions under a 25% continuing harvest of littleneck sized clams. Recovery curves are: R – model broodstock/recruitment curve relaxed (more recruits than average) by 10%, and C – model broostock/recruitment curve constrained (fewer recruits than average) by 10%. Symbols are 0–99–25 = no fishing for 10 y, 99% fishing for 10 y, 25% fishing for recovery period.

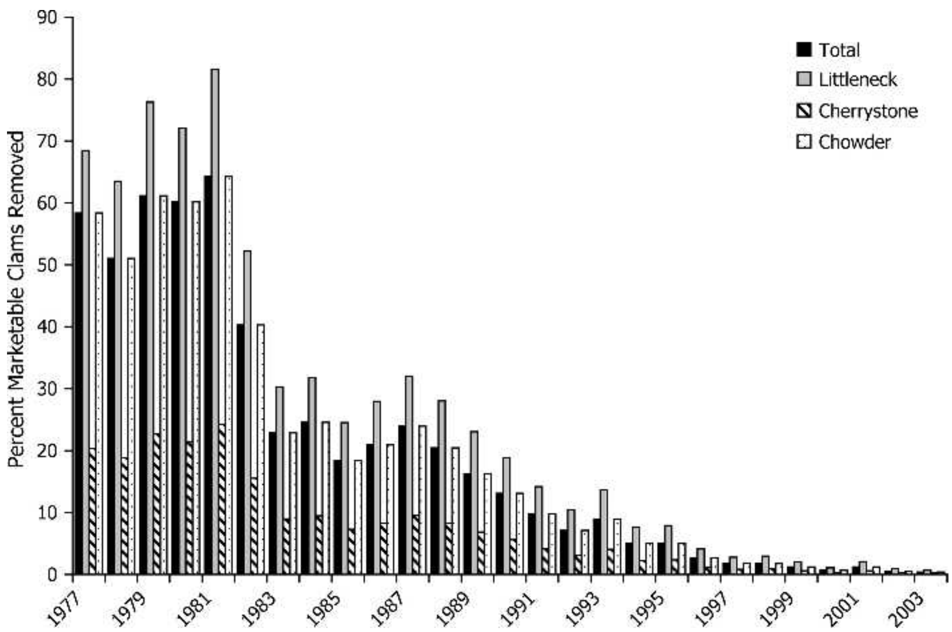

Figure 12. Percentage of market clams removed from the Town of Islip population based on harvest data and fishery independent survey data.

statistically significant. The drop in either growth and/or clam populations were believed to have been severe enough to cause the Bluepoints Company (who had historic rights to about 13,000 acres of bay bottom) to announce and abandonment of their hard clam aquaculture business, and in 2002 the parent company donated all but about 1,500 acres of land to The Nature Conservancy. Evidence for a significant decline in growth is lacking (Laetz 2002).

The importance of the recruit-per-adult production curve (Fig. 7), and the relatively low recruitment success of hard clams cannot be overemphasized in the interpretation of recent results. Whereas based on data from GSB, the data on egg production of larger clams are limited (Eversole 2001). In the GSB population, an average of 30% of the total population (60% of adults) was in the littleneck size range. Based on the biomass-egg production curve, and their abundance, these individuals collectively were responsible for a significant portion of the egg production. This relationship is important for management of hard clam populations. Harvest concentrated on cherrystone and chowder sizes may have little net effect on

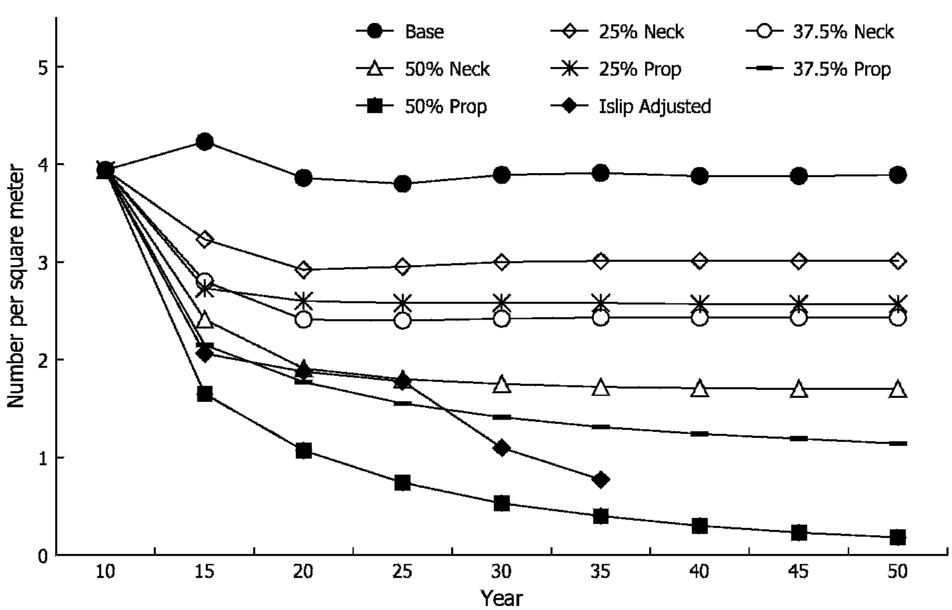

Figure 13. Simulated effects of a fishery removing clams in proportion (Prop) to their size abundance in the population at various percentages of fishing intensity. Base = base conditions with no fishery. Islip landings data (Islip adjusted) for the 1978–2003 period were adjusted to the base model case of 4 market sized clams per square meter to facilitate comparisons.

reproductive output. They are a relatively small fraction of the population and they require high levels of food to produce significant quantities of gametes. This is why proportional fishing creates greater declines in numbers and biomass at lower percentage levels of exploitation. Through time, the relative abundance of the smaller individuals tends to increase, and if these individuals are over-exploited the fishery is not only reducing the population, but it is greatly reducing the reproductive potential. Because the population of larger animals is small, and their reproductive output, on a biomass basis, in years of poor food conditions is low. A population modeled with sequential years of poor environmental can collapse, particularly if there is continued heavy fishing mortality.

Whereas the population is now at a low level, the decline is not unprecedented. Kellogg (1901) indicates that: "In many localities where it [hard clam] has been taken most abundantly, the failure has become alarming." For Islip in particular he notes that the hard clam "has always been the center of the industry in the bay," that five years previously the supply to the canning factory (using 400 bu d^{-1}) began to decrease, and that "2 years ago it became impossible to obtain clams." "The markets at Babylon, Amityville, Massapequa, and Freeport had also been quite extensive, but all report the same very recent failure of the little-neck in the Great South Bay."

To investigate the potential for harvest from the Islip portion of GSB under base conditions the results from year 50 of the simulations (40 y after the initial 10 y model stabilization) were combined with market prices. Both numbers of adults m^{-2} and dry meat weight m^{-2} had stabilized or showed a consistent downward trend by simulated year 50. The effects of the various percentage removals on standing stock, standing stock biomass, given per m^{-2}, and Islip revenue illustrate the differences with the varying fishing simulations (Fig. 14). A simulated 25% proportional fishery yielded the greatest monetary return per square meter and for the bay. This fishery also created the largest drop in population numbers and biomass for any fishery at a 25% exploitation level. Monetary yields for littleneck fisheries were nearly the same at both 37.5% and 50% exploitation levels because the higher level fishery caused such a great drop in numbers and biomass that it required fishing a larger area of the bay for the same yield. It is immediately apparent that a proportional fishery above 25%, or a littleneck

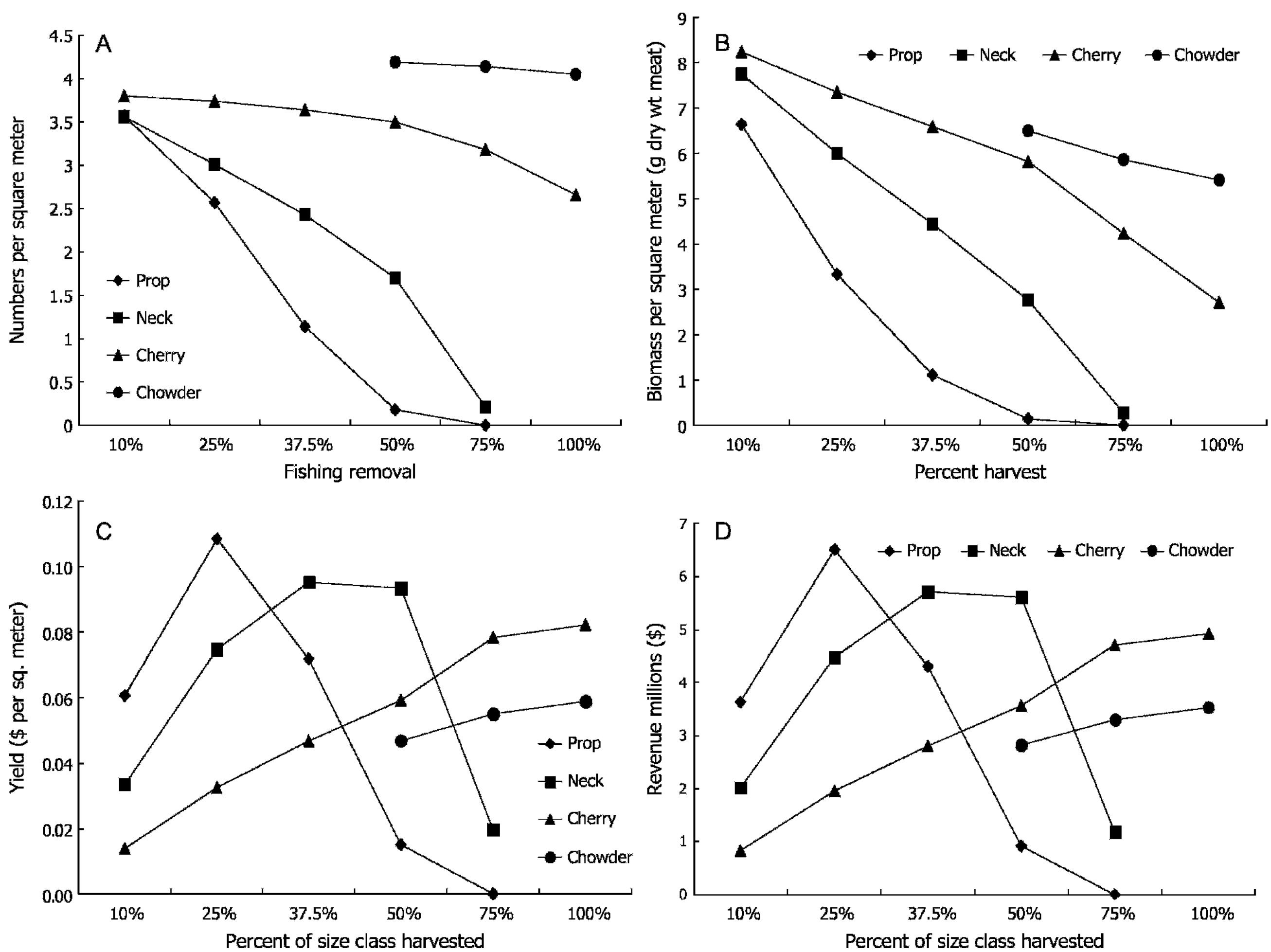

Figure 14. Simulated effects of fishing on various parts of the hard clam populations after 50 y. Percentages = the percent of population removed per year under various fishing scenarios. Prop = fishery removing clams in proportion to their size abundance in the population. Neck = fishery removing only littleneck sized clams. Cherry = fishery removing only cherrystone sized clams. Chowder = fishery removing only chowder sized clams. (A) number of clams m^{-2} remaining, (B) Biomass (g dry wt meat m^{-2}) remaining, (C) Monetary yield m^{-2}, and (D). Monetary yield for certified Islip town waters. Note that lines connecting data are to ease comparisons across fishing rates and do not imply a linear change in abundance, yield or value.

fishery above 37.5% begins to dramatically lower both numbers (Fig. 14a) and biomass (Fig. 14b) for little or no economic gain (Fig. 14c and d). The revenue from a topneck only fishery was not computed because of the difficulty in establishing a price for this size category, but it would probably lie somewhere between a littleneck and cherrystone only fishery.

The values per square meter for both cherrystone and chowder simulations continued to rise as a greater percentage of the size class was harvested. This implies harvesting 75% to 100% of the bay bottom to obtain a smaller monetary return than a 25% removal of a proportional fishery or a 37.5% littleneck fishery (Fig. 14c). These figures do not include costs, and it is unlikely that any clam fishery could profitably harvest at these levels.

The only way to harvest a high proportion of littleneck clams and maintain biomass is to remove 37.5% or less of the adult standing stock (Fig. 14b), and this would yield approximately \$0.095 annual revenue m^{-2} of bay bottom harvested. The Islip region covers approximately 56,000,000 m^{-2} of waters certified for harvesting. This area could yield nearly \$5.3 million in annual revenue under the simulated conditions. Even a 10% littleneck fishery would produce \$1.88 million in annual value (Fig. 14d). Proportional fisheries increase the pressure on the stocks, but at 25% harvest, this fishery could yield nearly \$6.1 million per year. It is important to remember that these simulations represent constant equitable conditions for hard clam stocks and thus harvest levels would have to be somewhat lower than suggested above to provide the population resilience in a single or a series of poor years. Augmentation of the stocks by aquaculture, particularly on leased ground might greatly increase the potential return. For example, aquaculture yields of 25 littlenecks m^{-2} at \$0.15 each would yield \$3.75 in revenue. It would take nearly 40 m^{-2} of natural harvest to reach the same level of revenue. Costs, of course would be higher with the aquaculture option.

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